

Population of ^{13}Be in a Nucleon Exchange Reaction

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The neutron-unbound nucleus ^{13}Be was populated with a nucleon-exchange reaction from a 71 MeV/u secondary ^{13}B beam. The decay energy spectrum was reconstructed using invariant mass spectroscopy based on ^{12}Be fragments in coincidence with neutrons. The data could be described with an s -wave resonance at $E_r = 0.73(9)$ MeV with a width of $\Gamma_r = 1.98(34)$ MeV and a d -wave resonance at $E_r = 2.56(13)$ MeV with a width of $\Gamma_r = 2.29(73)$ MeV. The observed spectral shape is consistent with previous one-proton removal reaction measurements from ^{14}B .

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I. INTRODUCTION

Recent experimental investigations of the level structure of the neutron-unbound nucleus ^{13}Be agree about the overall strength distribution of the excitation energy spectrum [1–6], but there is no consensus on its interpretation. While there seems to be general agreement about the presence of a broad s -wave resonance below 1 MeV and a d -wave resonance at 2 MeV, the composition of the observed peak around 500 keV, as well as the decay paths of the d -wave resonance, are still being discussed. Earlier reports of a narrow low-lying s -wave state [7, 8] have been attributed to a sequential decay from the first excited 2^+ state in ^{14}Be to ^{12}Be [3, 6, 9].

In 2010, Kondo *et al.* [3] reported a low-lying p -wave resonance at 510(10) keV populated by a one-neutron removal reaction from ^{14}Be at 69 MeV/u. However, a recent analysis of these data, as well as a new measurement at a higher beam energy on a hydrogen target (304 MeV/u), preferred an interpretation which fits the ~ 500 keV peak with only two interfering broad s -wave resonances [4, 5]. Moreover, the presence of additional p - or d -wave strength could not be ruled out, indicating that an $\ell \neq 0$ resonance around 1 MeV might exist [5]. The fits in both papers included a significant decay branch of the $d_{5/2}$ state to the first excited 2^+ state in ^{12}Be .

While neutron-removal reactions are expected to populate positive as well as negative-parity states, proton-removal reactions should be more selective and populate

only positive-parity states. Randisi *et al.* [6] measured the decay energy spectrum of ^{13}Be following the one-proton removal reaction from ^{14}B at 35 MeV/u and argued that the ~ 500 keV peak consists of an s -wave resonance as well as a low-lying d -wave resonance. In addition, Randisi *et al.* searched for the decay of the $d_{5/2}$ resonance at 2 MeV to the first excited 2^+ state in ^{12}Be by measuring the γ -rays from this state in coincidence. No significant branch of this decay mode was observed.

In the present work, the nucleon-exchange reaction ($-1p+1n$) from ^{13}B was used to populate states in ^{13}Be . Similar to the proton-removal reaction it is expected to only populate positive-parity states. This type of reaction has been shown to have sizable cross sections at intermediate beam energies. For example, the one-proton removal–one-neutron addition ($-1p+1n$) reaction has been utilized with stable (^{48}Ca) as well as radioactive (^{48}K and ^{46}Cl) beams to explore the structures of ^{48}K , ^{48}Ar , and ^{46}S [10]. The inclusive cross sections were 0.13(1) mb and 0.057(6) mb for the $^9\text{Be}(^{48}\text{K}, ^{48}\text{Ar})$ and $^9\text{Be}(^{46}\text{Cl}, ^{46}\text{S})$, respectively. This ($-1p+1n$) reaction was also used for the first time to measure neutron unbound states in the study of ^{26}F populated from a 86 MeV/u ^{26}Ne beam [11].

II. EXPERIMENTAL SETUP

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A 120 MeV/u ^{18}O primary beam from the Coupled Cyclotron Facility bombarded a 2.5 g/cm² ^9Be production target. The A1900 fragment separator was used to separate and select the ^{13}B secondary beam. The final energy of the beam was 71 MeV/u, with an intensity of

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approximately 8×10^5 particles per second and a purity of 96%. The ^{13}B beam impinged upon a 51 mg/cm^2 ^9Be target where ^{13}Be was produced in a nucleon-exchange reaction and immediately decayed into $^{12}\text{Be} + n$.

The ^{12}Be reaction products were deflected by a large-gap sweeper magnet [12] and identified from energy-loss and time-of-flight measurements. The ^{12}Be energy and momentum vectors were reconstructed from position information and a transformation matrix based on the magnetic-field map using the program COSY Infinity [13]. Coincident neutrons were measured with the Modular Neutron Array (MoNA) [14, 15] and the Large-area multi-Institutional Scintillator Array (LISA). The energy and momentum vectors of the neutrons were determined from the positions of the neutron interactions in the arrays and the time-of-flight between the arrays and a scintillator located upstream near the target. The nucleon-exchange data were recorded simultaneously with the data for the one proton-removal reaction populating unbound states in ^{12}Be . These results have been published recently in Ref. [16] where further details of the experimental setup and analysis can be found.

III. DATA ANALYSIS

The decay energy spectrum of ^{13}Be was reconstructed by the invariant-mass method and is shown in Figures 1 and 2. The spectrum shows the same general features as the previous measurements with a strong peak around 500 keV and an additional structure at about 2 MeV. The energy dependent resolution (blue-dotted line) and the overall efficiency (red solid line) are shown in the insert of Figure 1.

In order to interpret the measured decay-energy spectrum, Monte Carlo simulations were performed with the incoming beam characteristics, reaction mechanism, and detector resolutions taken into account. The neutron interactions within MoNA-LISA were simulated with GEANT4 [17, 18] using the MENATEL package [19] as described in Ref. [20]. Resonances were parameterized using energy-dependent Breit-Wigner line shapes [16].

The present nucleon-exchange reaction is expected to populate the same positive-parity states that were populated in the one-proton removal reaction. In that case, the valence neutron configuration of the ^{14}B projectile is dominated by $\nu 2s_{1/2}$ and $\nu 1d_{5/2}$ components and states with the same configurations are expected to be populated in ^{13}Be by proton removal [6]. The ground state of ^{13}B has spin and parity of $3/2^-$ dominated by a $(\pi 1p_{3/2})^3$ proton configuration and a closed sp shell neutron configuration. Removing the odd proton from ^{13}B is similar to the proton removal from ^{14}B while the added extra odd neutron will populate states in the open sd shell.

Randisi *et al.* was able to fit their data from the proton-removal reaction based on selectivity arguments with only two components, an s -wave resonance at $E_r = 0.70(11)$ MeV with a width of $\Gamma_r = 1.70(22)$ MeV and a

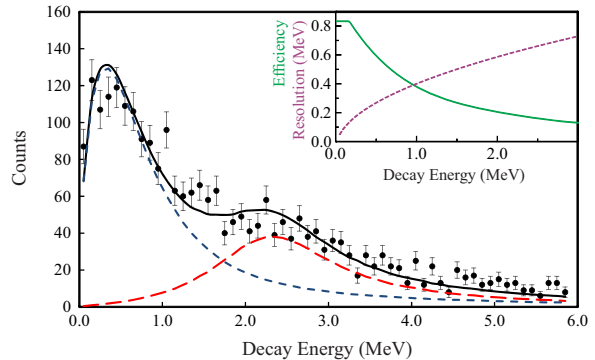


FIG. 1. (color online) Decay-energy spectrum of ^{13}Be fit with two components. The solid black line is the sum of simulated decay-energy spectra from an s -wave resonance (short-dashed blue line) and a d -wave resonance (long-dashed red line) with parameters listed in the text. The insert shows the energy dependent resolution (dotted purple line) and the overall efficiency (solid green line).

d -wave resonance at $E_r = 2.40(14)$ MeV with a width of $\Gamma_r = 0.70(32)$ MeV [6]. The best fit to the decay-energy spectrum from the present nucleon-exchange reactions is shown in Figure 1 with an s -wave resonance at $E_r = 0.73(9)$ MeV with a width of $\Gamma_r = 1.98(34)$ MeV and a d -wave resonance at $E_r = 2.56(13)$ MeV with a width of $\Gamma_r = 2.29(73)$ MeV. Overall these parameters agree with the results from Randisi *et al.* with only the width of the d -wave resonance being somewhat larger.

The overall cross section for populating ^{13}Be with the $(-1p+1n)$ reaction was extracted to be $0.30(15)$ mb which is about an order of magnitude smaller than one-proton removal reactions on neutron-rich p -shell nuclei. Kryger *et al.* reported a cross section of $2.46(3)$ mb for the proton removal from ^{16}C to ^{15}B [21] and Lecouey *et al.* measured $6.5(15)$ mb for the proton removal reaction from ^{17}C to ^{16}B [22].

The cross section is somewhat larger than the cross section of 0.1 mb estimated for the charge-exchange reaction based on Distorted Wave Born Approximation (DWBA) calculations using the code FOLD [25]. Transition densities that were input to FOLD were calculated using the shell-model code OXBASH [26]. The CKII interaction [27] was used in the p -shell model space to calculate the transition densities for the ^9Be - ^9B system, and the WBP interaction [28] was used in the $spdpf$ -shell model space to calculate the transition densities for the ^{13}B - ^{13}Be system. The effective nucleon-nucleon interaction of Ref. [29] was double-folded over the transition densities to produce form factors. Optical-model potential parameters were taken from Ref. [30].

Guided by $(0-3)\hbar\omega$ shell model calculations Randisi

TABLE I. Resonance parameters for the three-component fits. For each state with the proposed spin and parity (J^π) shown, the resonance energy (E_r), resonance width (Γ_r), and the population relative to the $1/2^+$ state ($I/I_{1/2^+}$) are listed for the proton-removal reaction of Randisi *et al.* ($-1p$) [6] as well as the present nucleon-exchange reaction ($-1p+1n$).

J^π	E_r	Γ_r	$I/I_{1/2^+}$	E_r	Γ_r	$I/I_{1/2^+}$
		Randisi <i>et al.</i> [6] (−1p)		present work (−1p+1n)		
1/2 ⁺	0.40±0.03	0.80 ^{+0.18} _{−0.12}	1.00	0.40 ^a	0.80 ^a	1.00
5/2 ₁ ⁺	0.85 ^{+0.15} _{−0.11}	0.30 ^{+0.34} _{−0.15}	0.40±0.07	1.05±0.10	0.50±0.20	0.63±0.15
5/2 ₂ ⁺	2.35±0.14	1.50±0.40	0.80±0.09	2.56±0.13 ^b	2.29±0.73 ^b	3.88±0.50

^a fixed value from Randisi *et al.* [6]

^b value taken from two-parameter fit

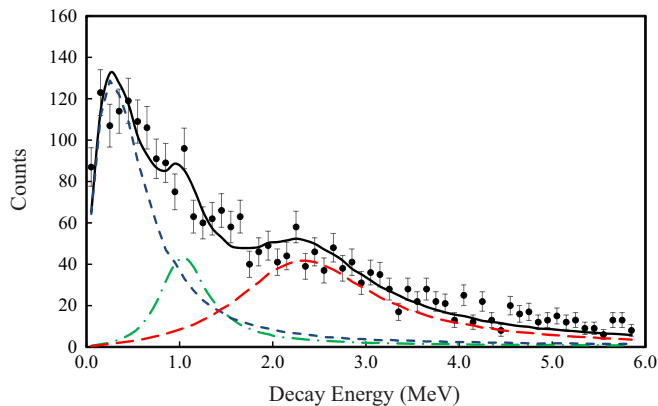


FIG. 2. (color online) Decay-energy spectrum of ^{13}Be fit with three components. The solid black line is the sum of simulated decay-energy spectra from an s -wave resonance (short-dashed red line) and two d -wave resonances (long-dashed red line and dot-dashed green line) with parameters listed in the text.

et al. analyzed their data by introducing a second lower-lying d -wave resonance [6]. The resonance energies and widths for this analysis are listed in Table I together with the parameters used to fit the present data as shown in Figure 2. A completely unconstrained three-resonance fit resulted in degenerate values for the lower two resonances. Thus the values for the s -wave resonance was constrained to the value of Randisi *et al.* ($E_r = 0.40$ MeV, $\Gamma_r = 0.80$ MeV) and the parameters for the second d -wave resonance were kept at the value extracted from the two-parameter fit ($E_r = 2.56$ MeV, $\Gamma_r = 2.29$ MeV). The resonance energy and width of the first d -wave resonance as well as strength of all three components were varied. Figure 2 shows that the nucleon-exchange data can be well described with parameters similar to the one-proton removal reaction.

Table I also includes the ratios of the d -wave resonances relative to the s -wave resonance for the two reactions. The relative intensities in the proton-removal reaction are governed by the ground state configuration of ^{14}B where the spectroscopic factors for populating the $1/2^+$, $5/2_1^+$, and $5/2_2^+$ were calculated within the WBP shell model to be 0.41, 0.13, and 0.43, respectively, in good

agreement with the data [6]. The $1/2^+$ and $5/2_2^+$ states are dominated by single-particle configurations, whereas the $5/2_1^+$ has $2\hbar\omega$ $^{10}\text{Be} \otimes (\nu 2s1d)^3$ parentage.

The intensity of the low-lying d -wave resonance in the nucleon-exchange reaction is slightly larger than the intensity extracted from the proton-removal reaction, while the intensity of the second d -wave resonance is significantly larger. These ratios do not have to be the same for the two different reactions. For example, in addition to the two $5/2^+$ states, the $(0-3)\hbar\omega$ shell model calculations also predict a low-lying $3/2^+$ state. The spectroscopic factor of this state for proton removal from ^{14}B is zero, so it is not expected to be observed in the data of Randisi *et al.* [6]. It could, however, be populated in the present reaction which would reduce the strengths of the two d -wave resonances relative to the low-lying s -wave resonance. It should be mentioned that the low-lying $3/2^+$ and $5/2^+$ states predicted by the $(0-3)\hbar\omega$ shell-model calculations using the WBP interaction [6] are not present in the simplified scheme by Fortune [23]. This discrepancy has recently been reiterated and is not fully understood [24].

Finally, the present data show no evidence for any low-energy decay from the second $d_{5/2}$ to the first excited 2^+ state in ^{12}Be as was suggested by Aksyutina *et al.* [5]. Simulations including such a decay branch resulted in an upper limit of less than 10%. This finding is consistent with results by Randisi *et al.* who extracted a branching ratio of 5(2)% [6].

IV. SUMMARY AND CONCLUSION

In conclusion, the $^{13}\text{B}(-1p+1n)$ nucleon-exchange reaction was used to populate the neutron-unbound nucleus ^{13}Be . The decay-energy spectrum can be described with resonance parameters similar to previously reported values for the proton-removal reaction from ^{14}B . In general nucleon-exchange reactions offer an alternative reaction mechanism to selectively populate states in neutron-rich nuclei when the nucleus of interest can not be populated by single proton (i.e. ^{15}Be , ^{20}B , or ^{24}N) or even two-proton (^{23}C) removal reactions.

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